



Extreme Weather Within the Context of Our Changing Climate

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Introduction

Chairman Boxer, Ranking Member Vitter and distinguished members of the Senate Environment and Public Works Committee – thank you for the opportunity to present today. It is a privilege and an honor to testify on this important topic.

I am Heidi Cullen and I currently serve as Chief Climatologist at Climate Central. Climate Central is an independent organization of scientists and journalists who research and report on climate and energy. Climate Central surveys and conducts scientific research on climate change and informs the public of key findings. Our scientists publish in peer-reviewed literature and our journalists report on climate science, energy, sea level rise, wildfires, drought, and related topics. Climate Central does not lobby, or support any specific legislation, policy or bill. I am also a Senior Research Fellow at the Wharton Risk Management and Decision Processes Center at the University of Pennsylvania. Assessing and communicating the risks of climate change is something I care deeply about.

Climate change was for a long time thought to be an issue for the distant future. But I am here today to testify that it has, in many respects, moved into the present. The impacts of human-caused climate change are being observed right here and right now in our own backyards and neighborhoods.

My testimony today draws from peer-reviewed literature and is an attempt to concisely review the following:

1. The science of extreme weather and climate change.
2. The so-called global warming hiatus of the early 2000s.
3. The important role of oceans in our climate system.

1. The Big Picture

When it comes to climate change, scientists focus on carbon dioxide (CO₂) because it is the most important long-lived global warming gas. CO₂ is emitted via human activities including fossil fuel burning, cement production and deforestation. Once emitted, a molecule of CO₂ can remain in the atmosphere for hundreds of years. Global CO₂ emissions reached a record high of 35.6 billion tons in 2012 (Peters et al., 2012). Carbon dioxide and other greenhouse gases warm the planet by absorbing the sun's energy and preventing heat from escaping back into space. The latest carbon dioxide emissions continue to track the high end of emission scenarios (Figure 1). Without significant emissions reductions, the world's average temperature could climb as much as 7 to 11°F by 2100 (Peters et al., 2013).

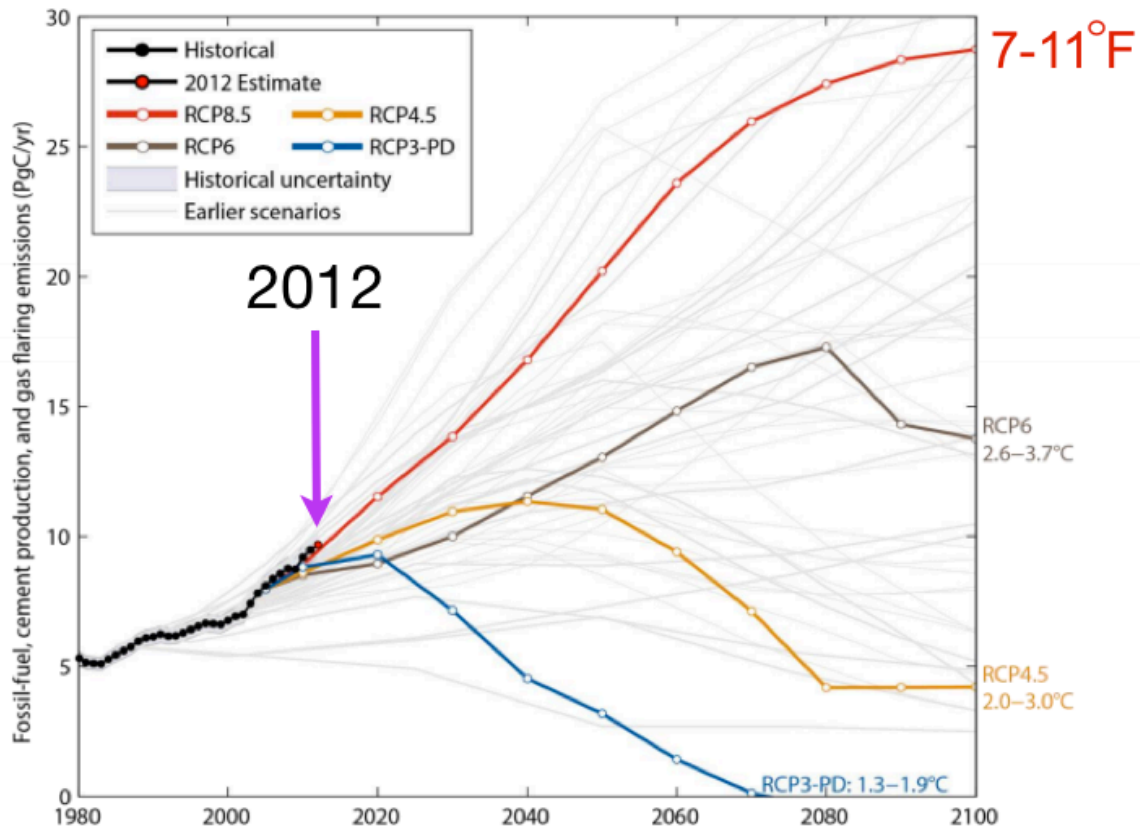


Figure 1: Observed emissions (black dots) and emissions scenarios (colored lines). Source: Peters et al., 2013, Global Carbon Project¹.

This past May, the amount of carbon dioxide in the air exceeded 400 parts per million (ppm) for the first time in at least 800,000 years (Figure 2). The news marks a troubling milestone, showcasing the steady increase of human-caused CO₂ emissions over the past century. Additional lines of evidence including ice cores and ocean sediments, suggest this may be the highest atmospheric CO₂ concentration as far back as 15 million years (Tripati et al., 2009).

¹ <http://www.globalcarbonproject.org/carbonbudget/index.htm>

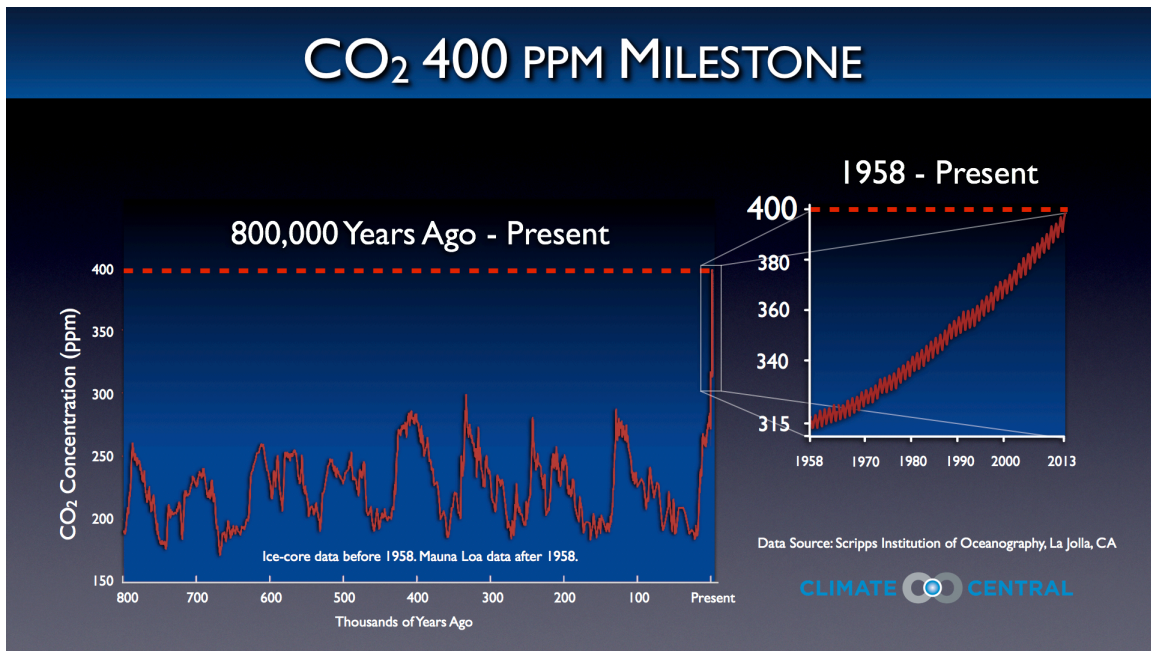


Figure 2: Carbon dioxide in the air exceeded 400 parts per million (ppm) for the first time in at least 800,000 years.

Across the globe, we are observing things we would not expect to observe in a climate controlled purely by natural variability. According to the National Oceanic and Atmospheric Administration (NOAA), 2012 was the 10th warmest year since records began in 1880. The annual global combined land and ocean surface temperature was 1.03°F above the 20th century average of 57.0°F. This marks the 36th consecutive year (since 1976 – during the presidency of Gerald R. Ford) that the yearly global temperature was above average. Currently, the warmest year on record is 2010, which was 1.19°F above average. Including 2012, all 12 years to date in the 21st century (2001–2012) rank among the 14 warmest in the 133-year period of record. Only one year during the 20th century—1998—was warmer than 2012.²

Despite this remarkable string of warmer-than-average temperatures, it is important to note that human-induced warming is superimposed on a backdrop of natural climate variations, meaning that the rise in temperature has not been, and will not be, smooth over space or time. There will still be cold spells, cool days, etc. for places just as we saw this past winter along the U.S. East Coast.

Here in the United States average temperatures have increased by roughly 1.5°F since record keeping began in 1895. More than 80 percent of this temperature increase has occurred since 1980. The most recent decade was the nation's warmest on record. Looking back, 2012 was an impressive year in terms of extreme weather and climate events. It was the warmest year on record in the lower 48 states. According to NOAA, the average temperature in the United States for 2012 was 3.2°F above the 20th-century average, and 1°F above 1998, the previous warmest year (Figure 3). The year also featured a massive drought, deadly heat waves that broke thousands of temperature records, and a

² <http://www.ncdc.noaa.gov/sotc/global/2012/13>

powerful Hurricane Sandy that devastated parts of the Mid-Atlantic and Northeast. The National Snow and Ice Data Center announced that Arctic sea ice had reached a new minimum extent that was drastically lower than the previous record, set in 2007, by an area about the size of Texas. Sea ice in the Arctic has also decreased dramatically since the late 1970s, particularly in summer and autumn. Since the satellite record began in 1978, minimum Arctic sea ice extent (which occurs in early to mid September) has decreased by more than 40 percent (NSIDC, 2012). This decline is unprecedented in the historical record and is consistent with human-induced climate change (Min et al., 2008; Kay et al., 2011).

There were 11 extreme weather and climate disasters in 2012 *each* costing upwards of \$1 billion. According to NOAA's National Climatic Data Center in Asheville, N.C., these billion-dollar events cost the United States a total of \$110 billion, which puts 2012 behind only 2005 on the list of costliest years since 1980 (Smith and Katz, 2013).

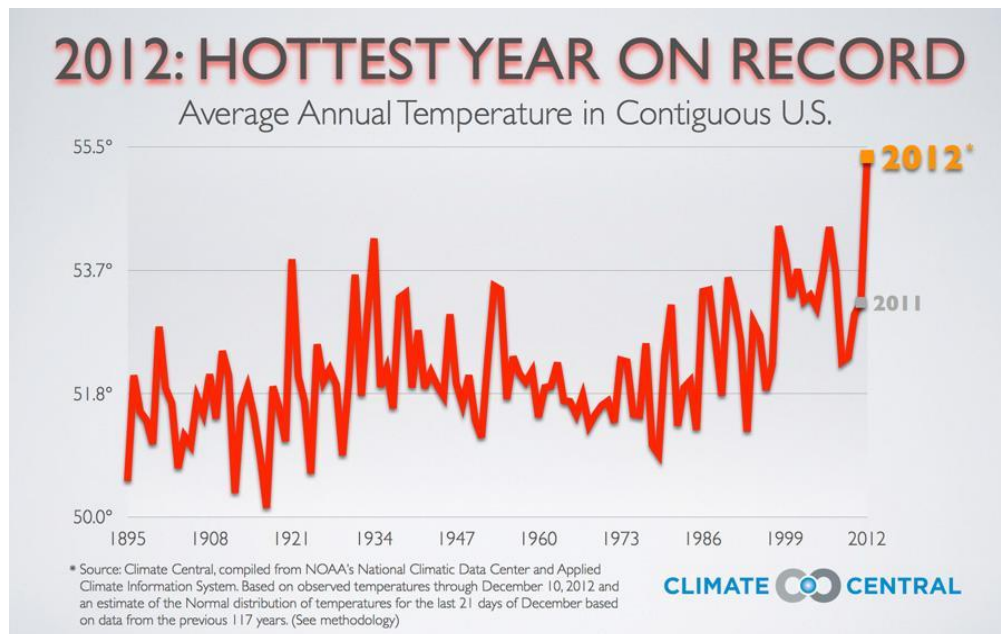


Figure 3: Average annual temperature in the contiguous United States.

Records continue to fall in 2013, with the continuation of drought conditions throughout the West. One of the greatest heat waves in North American history came in late June and peaked in early July, smothering states from Arizona to Washington state under a persistent "heat dome" of high pressure. It was during this heat wave that 19 firefighters lost their lives battling the Yarnell Hill fire in Arizona. The extraordinary heat wave, caused by an unusually extreme standing wave pattern in the jet stream, brought Earth's highest June temperature ever recorded on Sunday, June 30, when the mercury hit 129.2°F in Death Valley, Calif.

The seemingly endless string of extreme events has left many wondering if the weather here in the United States has fundamentally changed. Are we moving in the direction of ever more dangerous and costly extremes? The losses associated with these extreme events have raised questions about the overall vulnerability of our communities and the need to focus on pre-disaster resilience planning. The short answer to this first scientific question is yes.

We can already see the impacts of warming in certain types of extremes. The second question is a matter of policy. According to the Federal Emergency Management Agency (FEMA), every dollar spent on enhancing communities' ability to withstand extreme events reduces the cost of damage from such events by about \$4.³

1a. Extreme weather

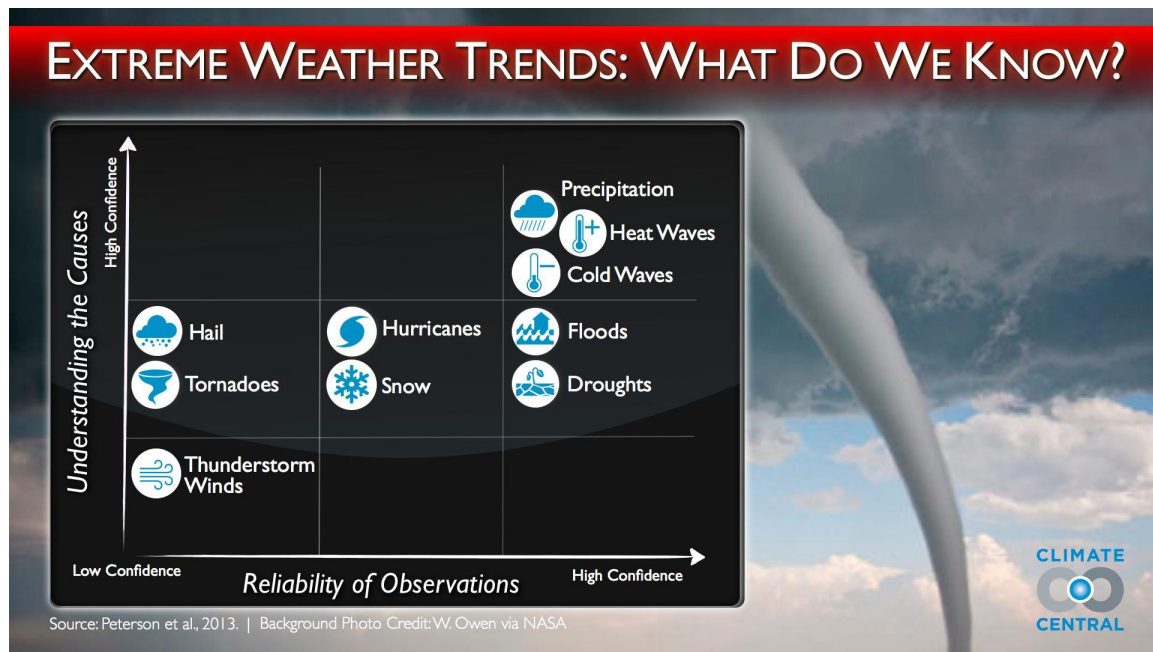


Figure 4: Our understanding of extreme weather events within the context of climate change is a function of the reliability of our observations coupled with our understanding of the causes of the extreme weather phenomenon. Source: Peterson et al., 2013.

The current state of the science on extreme weather trends is summarized in Figure 4. Our understanding of extreme weather events and trends within the context of climate change is a function of the reliability of our observations (e.g., how much data do we have about droughts?) coupled with our physical understanding of the causes of the specific extreme weather phenomenon (e.g., what causes a tornado or a heat wave?). There are certain types of extremes that we understand better than others and there are certain types of extremes for which we have better (wider coverage in space, longer records in time, and more accurate measurements) observational data than others. What follows is a summary of our understanding broken down by the type of extreme event.

- Heat Waves/Cold Waves

Periods of extreme heat and extreme cold can have profound societal, agricultural, economic impacts. Extreme heat ranks as the No. 1 weather-related killer in the United States (National Weather Service 2012; Borden and Cutter, 2008.) The scientific community has a solid physical understanding of heat waves and cold waves. Because our climate is warming, heat waves are expected to occur more often, while cold waves are expected to

³ <http://www.climatecentral.org/news/campaign-for-climate-resilience-spreads-at-local-level-16135>

decrease. In fact, recent decades tend to show an increase in the number of heat waves and a decrease in the number of cold waves, but over the long term, the drought years of the 1930s stand out as having the most heat waves (Figure 5). The chances of record-breaking high temperature extremes will continue to increase as the climate continues to warm. These results parallel the results of Meehl et al. (2009), who found that the current observed ratio of record high maximum temperatures to record low minimum temperatures averaged across the United States is about 2 to 1.

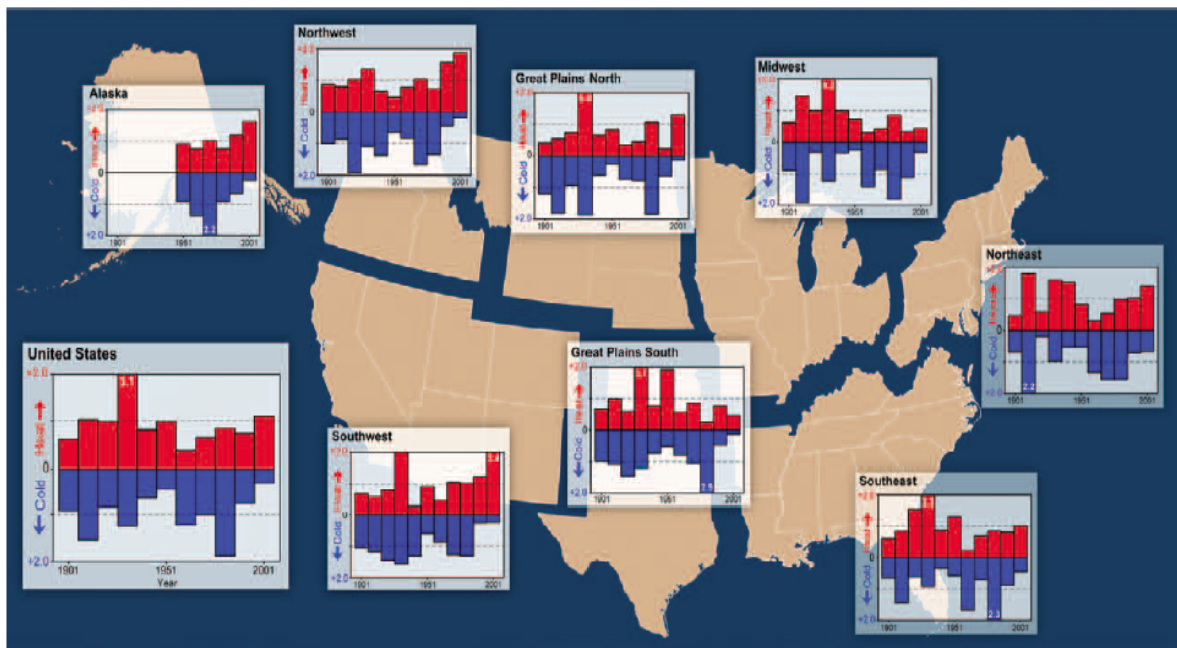


Figure 5: Time series of decadal-average values of heat wave (red bars) and cold wave (blue bars) indices from Peterson et al., 2013. Recent decades tend to show an increase in the number of heat waves and a decrease in the number of cold waves but, over the long term, the drought years of the 1930s stand out as having the most heat waves.

There has also been an increasing trend in persistently high nighttime temperatures. High overnight temperatures have broad negative impacts because they deprive people and animals from getting a reprieve from the heat, increasing the chances of heat-related illness. For a more specific example, the *State of the Climate in 2011* report, published by NOAA and the American Meteorological Society (AMS), looks at how human-induced global warming is influencing recent extreme weather and climate events. The report notes that global warming has already been playing a role in shifting the odds for several extreme events, including the 2011 Texas drought - the worst one-year drought in Texas history, costing nearly \$8 billion in agricultural losses⁴ - including the closing of a beef-processing plant in Plainview, Texas that employed 2,300 people⁵. The study concluded that human-induced climate change made the 2011 Texas heat wave and drought 20 times more likely than it would have been 50 years ago.⁶

⁴ <http://www.statesman.com/news/news/state-regional/drought-cost-texas-close-to-8-billion-in-agriculture/nRmNt/>

⁵ <http://www.nytimes.com/2013/02/28/us/drought-fells-a-texas-towns-biggest-employer.html?pagewanted=all&r=0>

⁶ <http://www.ncdc.noaa.gov/bams-state-of-the-climate/2011.php>

- Wildfires

The deadly Yarnell Hill fire that killed 19 elite firefighters in June played out, like other wildfires in the West this summer, in the midst of one of the most extreme heat waves on record, in combination with a prolonged drought. While the factors contributing to specific fires are varied and include natural weather and climate variability as well as human factors, such as arson, the National Climate Assessment found that human-induced climate change has already increased the overall risk of wildfires in the Southwest.

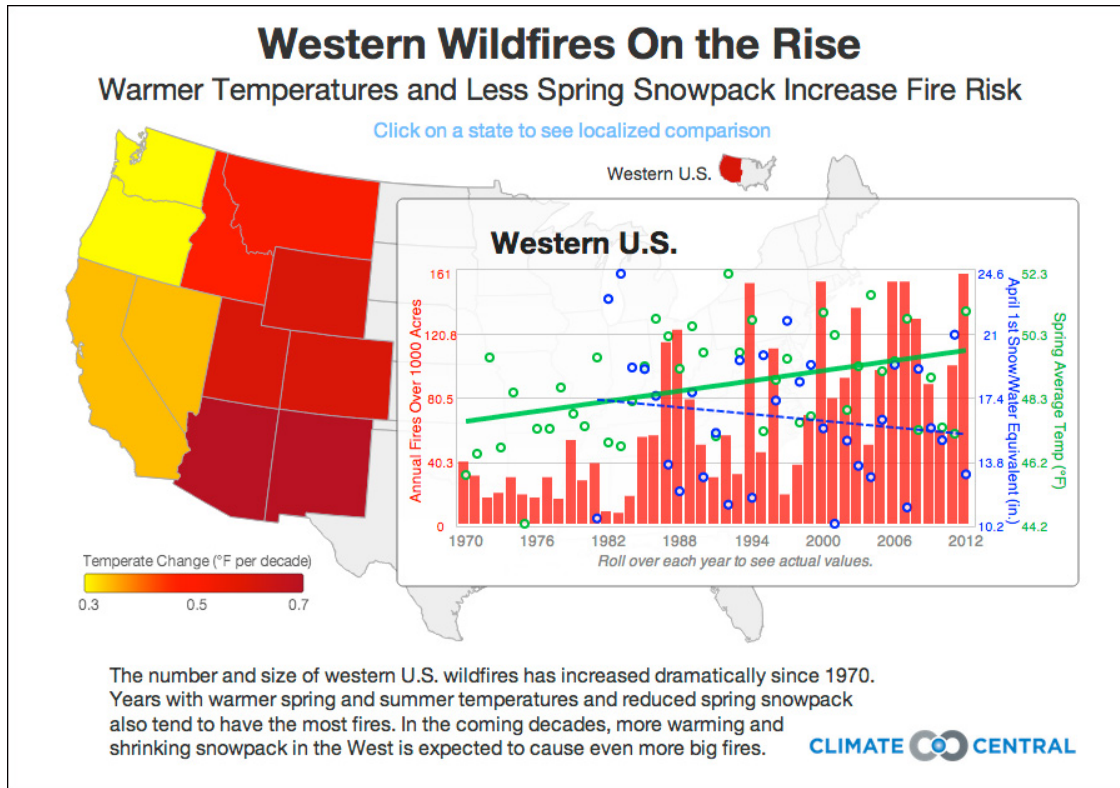


Figure 6: The number and size of western U.S. wildfires has increased since 1970.⁷

According to Climate Central research⁸, average spring and summer temperatures across 11 Western states have increased by more than 1.5°F since the 1970s (Figure 6). Spring temperatures in Arizona have warmed faster than any other state, rising nearly 1°F per decade since 1970, which has likely played a key role in Arizona's rapid increase in fires over the past two decades. The number of large fires burning each year in states like Arizona and Idaho have tripled or even quadrupled over that time. And in other states, including California, Colorado, New Mexico, Nevada, and Wyoming, the number of large fires has doubled. During the past decade there were seven times more fires greater than 10,000 acres each year in 11 Western states and nearly five times more fires larger than 25,000 acres each year, when compared to an average year during the 1970s. Years with

⁷ <http://www.climatecentral.org/news/rising-temps-shrinking-snowpack-fuel-western-wildfires-16222>

⁸ <http://www.climatecentral.org/news/report-the-age-of-western-wildfires-14873>

abnormally warm spring and summer temperatures tend to be years with more and bigger fires. Years with low spring snowpack (measured as the amount of water in snowpack on the ground as of April 1) also tend to be years with more fires. When there is a relatively thin snowpack come spring, it can melt quickly as the weather warms, leaving the forest drier earlier and much more likely to burn. Across the Southwest in particular, several recent years of below-average spring snowpack has extended the region's drought and fueled more big fires.

Overall, hotter and drier weather and earlier snow melt, coupled with land use changes and other trends, mean that wildfires in the West start earlier in the year, last later into the fall, threaten more homes, cause more evacuations, and burn more acreage. The growing season also starts earlier, so there is more to burn. According to Craig D. Allen, a research ecologist at the United States Geological Survey station at Bandelier National Monument in New Mexico, the fire season has lengthened substantially, by two months, over the past 30 years.⁹ Other factors contributing to the increase in wildfire trends include long-standing fire-suppression policies that have left many forests with substantial amounts of vegetation to serve as fuel, population growth, and more specifically, development in areas that have a history of wildfires, known as the "wildland-urban interface."

In 2009, The Quadrennial Fire Review projected that the effects of global warming would lead to "greater probability of longer and bigger fire seasons, in more regions in the nation." Specifically, climate change would result in shorter, wetter winters coupled with warmer, drier summers.¹⁰ Climate models used to predict future fire risks show an alarming increase in large wildfires in the West in coming years, as spring snowpack melts earlier, summer temperatures rise, and droughts occur more frequently and with greater intensity.

- Heavy Downpours/Floods/Drought

Heavy downpours are increasing nationally (Figure 7), especially over the past three to five decades. According to the National Climate Assessment (currently available in draft form¹¹) those events in the top 1 percentile of intensity have increased in every region of the contiguous United States since 1958 - with the largest increases occurring in the Midwest and Northeast and smallest increase occurring in the Northwest. The reason for these heavier rain events is relatively simple: in a world warmed by heat-trapping greenhouse gases, there's more evaporation, the atmosphere can hold more water vapor, and when that water vapor condenses as rain or snow, there's more of it available to fall. As a result, many flood management/storm water systems are not designed for 21st century rainstorms.

It is important to note that while the trend in intensity has been upward, it has not been steady. The record contains ups and downs from one decade to the next. This provides another example of the fact that human-caused climate change hasn't replaced natural climate variability: it appears on top of it. The frequency and intensity of extreme precipitation events are projected to increase throughout much of the country in the future.

⁹ <http://www.nytimes.com/2013/07/02/us/experts-see-a-hotter-drier-west-with-more-huge-fires.html>

¹⁰ http://www.iafc.org/files/wild_QFR2009Report.pdf

¹¹ <http://ncadac.globalchange.gov/>

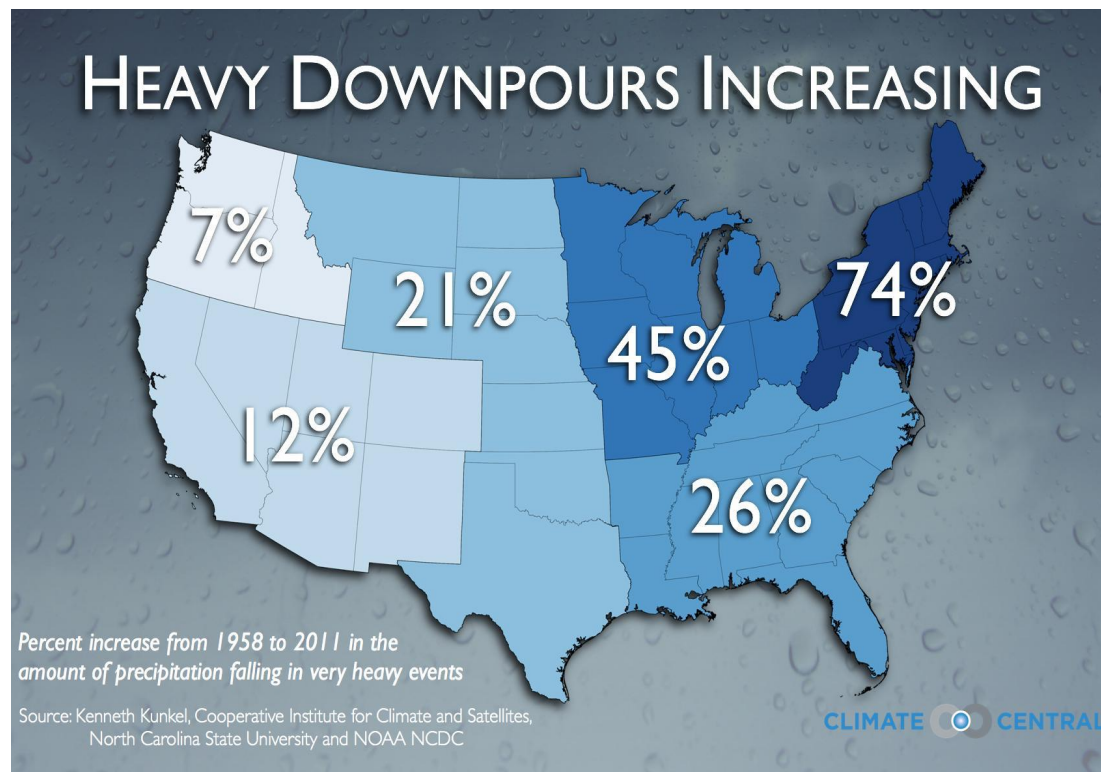


Figure 7: Percent increase from 1958 to 2011 in the amount of precipitation falling in very heavy events.

When it comes to understanding the causes of changes in floods and droughts, we don't know quite as much - even though we have good data. Overall, because of the way large-scale warming will affect the atmosphere, we expect to see dry regions become drier and wet regions become wetter. In general, the northern parts of the United States (especially the Northeast and Alaska) are projected to see more precipitation, while the southern parts (especially the Southwest) are projected to see less.

There is, however, evidence of a detectable human influence in the timing and magnitude of snowmelt and resulting streamflow in some western states (Barnett et al. 2008; Andersen and Shepherd, 2013). Changes in the magnitude of peak annual river floods are shown in Figure 8. Flooding in the northern half of the eastern Great Plains and much of the Midwest has been increasing, especially over the past several decades. Flooding has decreased in the Southwest, although there have been small increases in other western states. In the areas of increased flooding, increases in both total precipitation and extreme precipitation events are contributing to the flooding increases. In general, heavier rains lead to a larger fraction of rainfall running off and, depending on the situation, more potential for flooding. Floods are projected to intensify in most regions of the United States, even in areas where average annual precipitation is projected to decline, but especially in areas that are expected to become wetter, such as the Midwest and the Northeast.

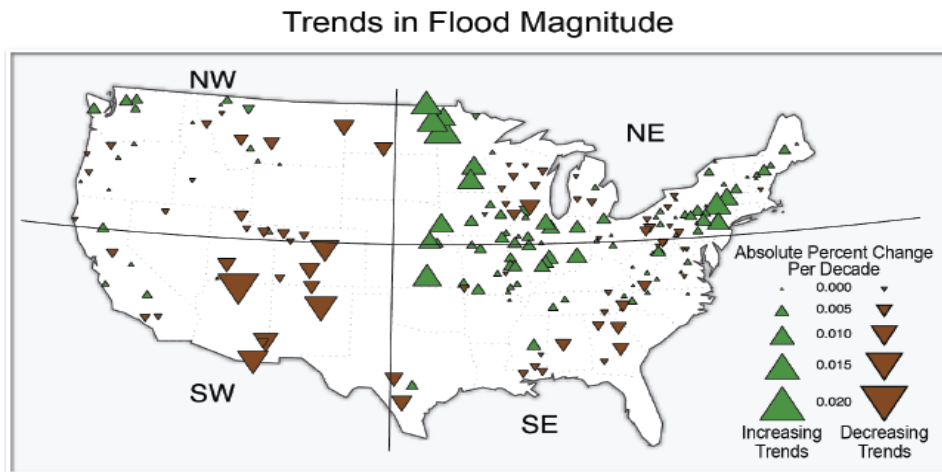


Figure 8: Trends in flood magnitude. Source: Hirsch and Ryberg, 2012.

Overall, precipitation has increased on average since 1900, with the largest increases the Midwest, southern Great Plains, and Northeast. Portions of the Southeast, the Southwest, and the Rocky Mountain states have experienced decreases. More winter and spring precipitation is projected for the northern United States, and less for the Southwest, during this century.

Examination of trends and variability of hydroclimatic conditions in the lower 48 states during the past century indicates that there has been a general drying across the western United States during recent decades (Figure 9). Precipitation has already declined in some areas within the Southwest and the Rocky Mountain states, and decreases in precipitation are projected to intensify in those areas and spread northward and eastward in summer. However, even in areas where precipitation does not decrease, projected higher air temperatures will cause increases in surface evaporation and loss of water from plants, leading to drier soils. As soil dries out, a larger proportion of the incoming heat from the sun goes into heating the soil and adjacent air rather than evaporating its moisture, resulting in hotter summers under drier climatic conditions.

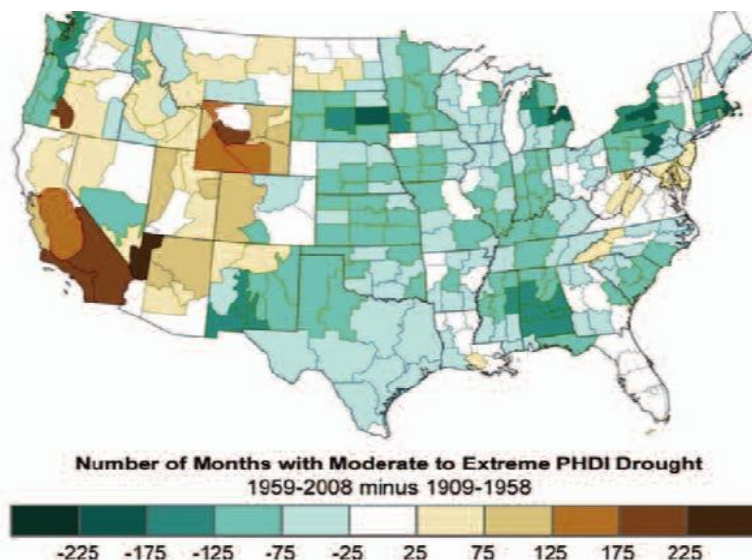


Figure 9: Geographic distribution of century-scale changes in droughts from Peterson et al., 2013.

- Sea Level Rise

Sea level rise is among the most serious potential consequences of global warming. Since 1880, sea level has risen approximately 8 inches around the world, on average, as a result of global warming. According to projections included as part of the draft National Climate Assessment, sea level could be as little as another 8 inches or as much as 6 feet 7 inches above 1992 levels by the end of the century. This high-end projection would put the homes of 7.8 million Americans today at risk of being flooded (Figure 10).

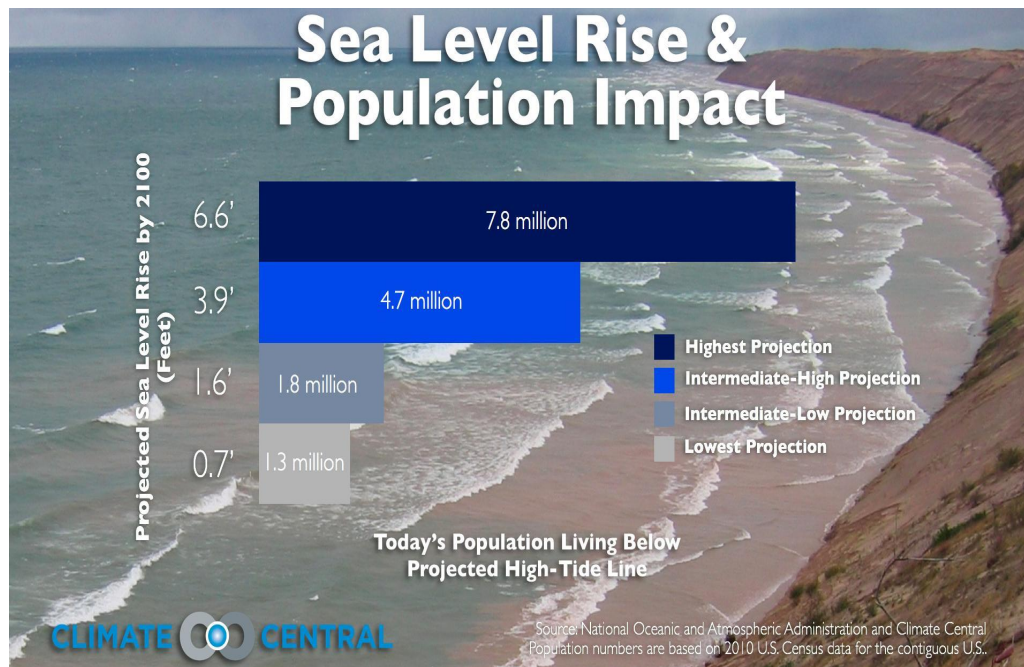


Figure 10: Potential population impacted (based on number of people currently living below the projected high-tide line) based on four sea level rise projections.

In the near term, sea level rise will be experienced as more coastal floods reach higher. Sea level rise due to global warming has already doubled the annual risk of extreme coastal flooding across widespread areas of the nation (Strauss et al., 2012). In some areas, especially for Louisiana, Texas, and mid-Atlantic states, sinking land will add to the rise and further exacerbate problems. All along the Pacific, from Seattle to the Oregon coast to San Francisco to Los Angeles, the component of past and mid-range projections of sea level rise from global warming more than triple the odds of “century” floods by 2030. The same is true inside the Chesapeake and Delaware Bays, and many sites to the north.

Sea level rise occurs for two reasons. First, water expands as it warms. As a result the ocean swells and rises. Second, more water is emptying into the ocean with each passing year as ice on mountaintops and ice sheets in Greenland and Antarctica continue to melt. It is still not known exactly how fast sea level will rise because 1) it is difficult to predict the dynamics of ice sheets collapsing and sliding into the sea and 2) it is not known exactly how much warmer the Earth’s temperatures will be in the future.

Sea level rise is already contributing to increased storm surge. A recent example of this was during Hurricane Sandy. At 13.88 feet, the storm tide (relative to Mean Lower Low Water) associated with Sandy set a record for Battery Park and inundation was widespread. A

recent estimate looked at the sea level rise component of Hurricane Sandy's storm surge and concluded that sea level rise caused Sandy to flood an area roughly 25 square miles greater than it would have in 1880 - increasing the number of people living on land lower than the storm tide by about 38,000 in New Jersey and about 45,000 in New York City (Strauss et al, 2012; Miller et al., in press).

- Hurricanes

By some measures, there has been a small increase in the overall strength of hurricanes and in the number of strong (Category 4 and 5) hurricanes in the North Atlantic since the early 1980s and a decrease in the eastern North Pacific (Figure 11). A recent paper (Emanuel, 2013) suggests that, contrary to previous findings, tropical cyclones are likely to become both stronger and more frequent in the years to come. The study found this is especially likely in the western North Pacific but also in the North Atlantic, where about 12 percent of the world's tropical cyclones occur each year.

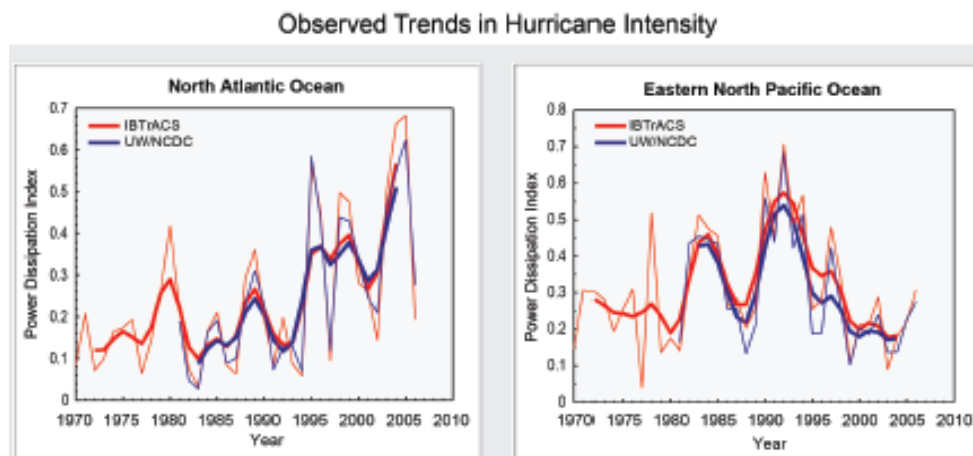


Figure 11: Observed trends in hurricane intensity. Source: National Climate Assessment draft report. Updated from Kossin et al., 2007).

However, a number of previous studies suggest that warming will cause tropical storms to be fewer in number globally, but stronger in force, with more category 4 and 5 storms (Knutson et al. 2010), which is worrisome since major hurricanes (Category 3 or greater) are responsible for the most damage. This consensus view was expressed most recently in a 2012 report from the U.N. Intergovernmental Panel on Climate Change (IPCC, 2012).

With regard to other types of storms that affect this country, winter storms have increased slightly in frequency and intensity, and their tracks have shifted northward over the United States.

It is not surprising that Superstorm Sandy raised questions about links to global warming. Sandy was the largest (diameter of tropical storm force winds extending out 1000 miles¹²) and second most destructive Atlantic hurricane on record. According to Dr. Jeff Masters at Weather Underground, New York City experienced its worst hurricane since the city's

¹² http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf

founding in 1624¹³. Sandy's 9-foot storm surge rode in on top of a high tide to bring water levels to 13.88 feet at The Battery (Figure 12), smashing the record 11.2 feet water level recorded during the great hurricane of 1821.

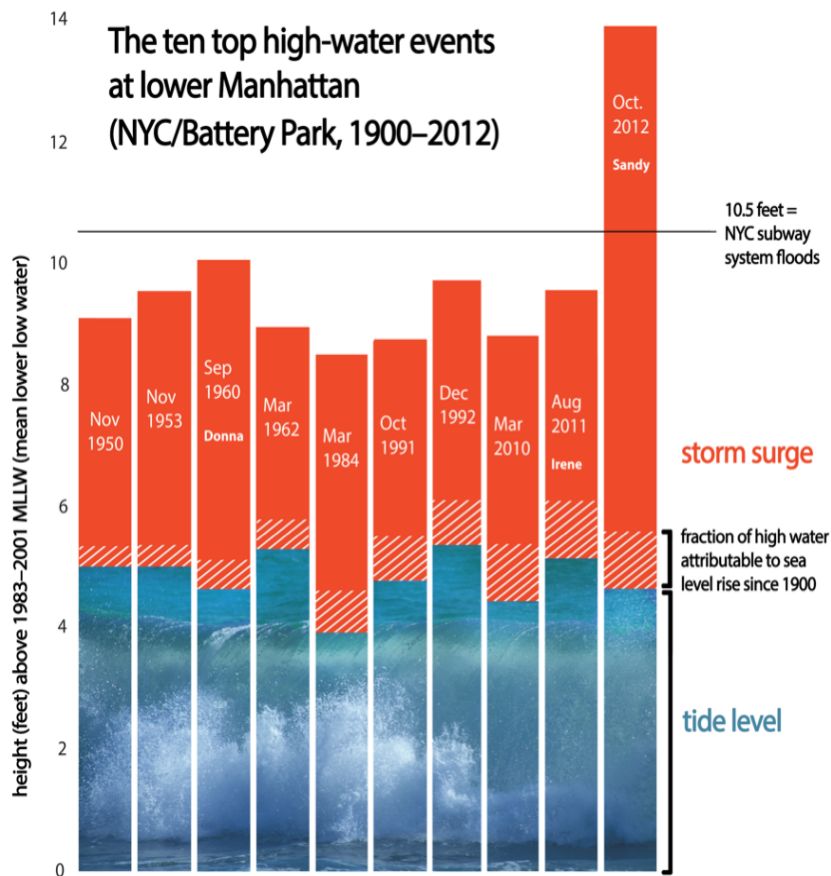


Figure 12: Top 10 high water events in lower Manhattan and fraction of high water attributable to sea level rise since 1900. Source: C. Calvin and B. Henson, UCAR.

There were three climate factors that helped shape Hurricane Sandy's unusual track and strength:

1. Ocean surface temperatures off the East Coast were running about 5°F above average during the summer of 2012. Global warming is contributing to warmer ocean temperatures.
2. Sea level rise gave the surge a higher launching pad than it would have had a century ago, making it more damaging than it otherwise would have been.
3. Upper-air flow over the Atlantic Ocean was temporarily jammed by a powerful area of high pressure near Greenland. It's possible that more frequent blocking events may be related to the loss of Arctic sea ice (Francis and Vavrus, 2012). This blocking affected Sandy's track.

¹³ <http://www.wunderground.com/blog/JeffMasters/article.html?entrynum=2282>

Sandy was indeed a very unusual storm. A recent study (Hall and Sobel, 2013) calculated that the occurrence rate of a Sandy-style storm is 0.0014 per year, meaning that if future hurricane activity matches the recent past we should expect a storm like Sandy on average about once every 700 years. The fact that this calculation shows Hurricane Sandy's track to be so rare under long-term average climate conditions implies either the New York–New Jersey area was simply unlucky or that a climate-change influence increased the probability of its occurrence.

- Tornadoes

Tornadoes are currently the least understood extreme weather event when examined within the context of global warming. Tornado data do not reveal any obvious trends in tornado occurrence or deaths that would suggest a clear link to global warming (Figure 13). A recent paper (Kunkel et al., 2013), found that the occurrence of EF-1 and stronger tornadoes on the Enhanced Fujita Scale has shown no trend since 1954. Similarly, there is no evidence to indicate that EF-4 and EF-5 tornadoes — like the one that devastated a large swath of Moore, Oklahoma in May — are becoming more frequent or severe. In general, it's hard to identify meaningful trends in historical tornado data due to changing reporting practices (e.g., the advent of advanced radar technology).

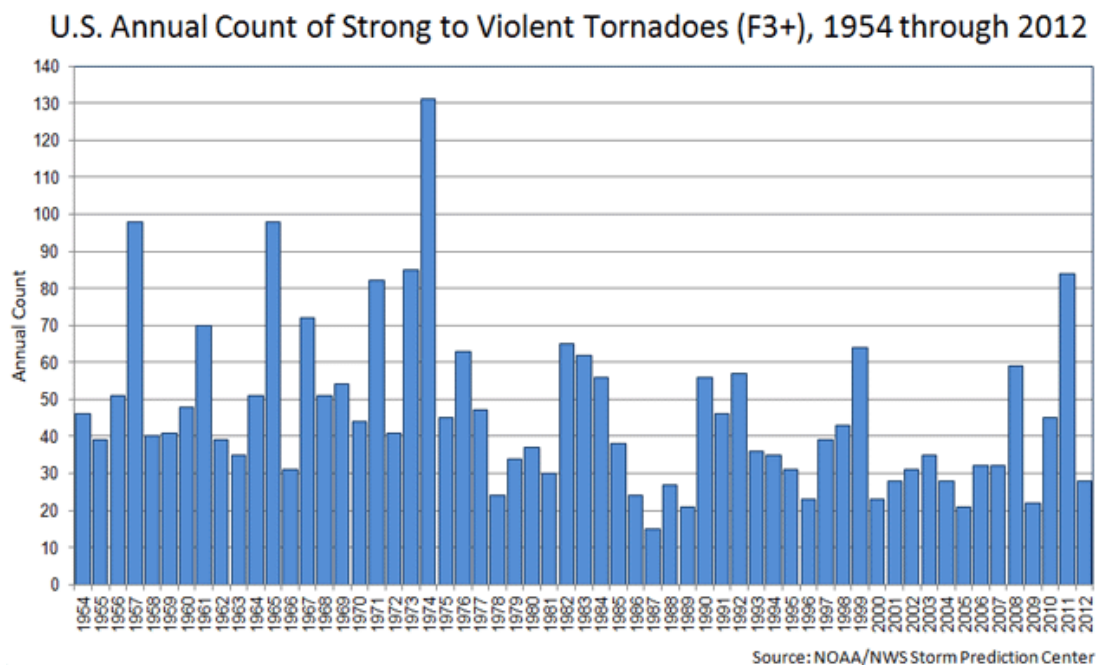


Figure 13: Number of annual EF-3 or greater tornadoes from 1954 to 2012. Credit: Storm Prediction Center.

Because historical tornado data is not considered very reliable or consistent, scientists have focused on how a warming climate might alter two of the basic ingredients that go into producing a tornado. First, you need warm, humid air beneath a layer of cool, dry air. Second, you need those layers to be traveling at different speeds or in different directions, a phenomenon called wind shear. These two conditions are common in the Plains states during the spring and early summer.

The jet stream pushes cool, dry air from the Rockies over slower-moving humid air from the Gulf of Mexico. When a disturbance like a cold front or a low-pressure system causes the two layers to interact, the hot layer tries to rise, and you get a rotating column of air that can turn into the sort of violent thunderstorm that sometimes spawns tornadoes.

Climate change will likely affect these two ingredients in opposite ways. On one hand, warmer air can hold more moisture than cool air can, so moisture content will increase with global temperatures. More moisture, plus higher temperatures may lead to more atmospheric instability and hence more thunderstorm activity.

On the other hand, wind shear is expected to decline as the Arctic warms. Most recent models point to higher moisture content resulting in more strong thunderstorms, but the lower wind shear means a smaller fraction of them will spawn tornadoes. Whether there will be so many more thunderstorms that they end up creating more net tornadoes, despite the lower wind shear, is unclear.

1b. What is causing the trend toward more extreme weather?

Ongoing research (Francis and Vavrus, 2012; Petoukhov et al., 2013) suggests a possible mechanism for the increasing extremes we are beginning to see. Specifically, by changing the temperature balance between the Arctic and mid-latitudes, rapid Arctic warming is altering the course of the jet stream, which is responsible for steering weather systems from west to east around the globe. The Arctic has been warming about twice as fast as the rest of the Northern Hemisphere, due to a combination of human emissions of greenhouse gases and unique feedbacks built into the Arctic climate system. According to this new research, the jet stream is becoming “wavier,” with steeper troughs and ridges. Weather systems are moving more slowly, increasing the chances for long-duration extreme events, like droughts, floods, and heat waves. The tendency for weather to get stuck in one pattern is going to favor extreme weather conditions.

2. Global Warming Has Not Stopped

Global warming has not stopped. It is important that we distinguish between global mean *temperature* and global *warming*. While the temperature rise in the atmosphere may have temporarily slowed, the warming continues to penetrate into every component of our climate system.

The human impact on our climate system is significant. Current greenhouse gas concentrations are trapping enormous amounts of heat into our climate system every day. Despite, a record warm year in 2012, a steady rise in atmospheric greenhouse gas concentrations and a continued uptick in extreme weather events, some have begun to question whether global warming has stopped. Despite the fact that all 12 years of the 21st century (2001-2012) rank among the 14 warmest in the 133-year period of record, it is true that the rise in global surface temperature has been slower over the past 15 years when compared with the rate of increase during the 1970s, 80s and 90s (Figure 14).

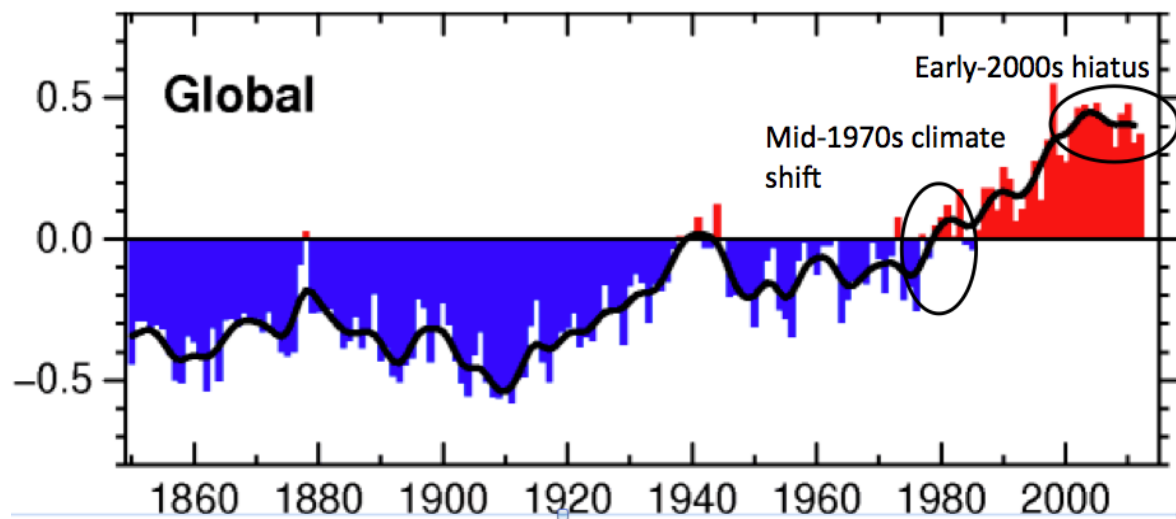


Figure 14: Global temperature anomaly from HADCRUT3. Courtesy: J. Meehl, NCAR.

First, this claim depends on the strategic selection of start and end points. The starting point for this so-called warming hiatus is almost always 1997-1998, a particularly warm period because of a strong El Niño. It is also important to note that the period contains several moderate-to-strong La Niña events, which tend to cool the planet slightly – including in 1999-2000, 2007-2008 and 2010-2011. The “early-2000s hiatus” is an area of active research that scientists are treating with extreme interest, as it is important to our understanding of the interplay between natural variability and human-induced warming, and also serves as a case study for improving the performance of our climate models. The active research question is focused on finding where the warming went and what possible sources of natural variations, resulting in a cooling effect, may have masked the warming.

A recent analysis of global ocean heat content measurements seem to have located the missing warming - in the deep ocean. Whereas upper ocean waters, from the surface to 2,300 feet depth, show no warming from 2004 to 2008, the waters from 2,300 to 6,500 feet show warming at an unprecedented rate. During the past decade, about 30% of the excess heat has been dumped into the deep ocean below 2,300 feet (Meehl et al., 2011; Balmaseda et al., 2013; Meehl et al., 2013). Ongoing research suggests that aerosols from a series of volcanic eruptions in the 2000s may also be playing a contributing role (Santer et al., in review).

3. The Important Role of the Oceans

It is important to keep in mind that there is much more to our climate system than our atmosphere. The oceans take up about a quarter of the CO₂ that we are putting into the atmosphere by fossil fuel burning and deforestation. The land surface takes up another quarter (Canadell et al., 2007).

Even more dramatic is the fact that the ocean absorbs more than 90 percent of the excess heat trapped by rising carbon dioxide levels (Church et al., 2011; Figure 15). This will continue until the surface ocean warms enough to balance the radiative forcing. This moderating effect of the ocean explains why there is 1°F of warming still in the pipeline

even if we stop adding CO₂ today. This is because water is both slower to warm and slower to release its heat than air. The process is no different than a cup of coffee. The coffee cools because it's releasing heat into the air above it, but the extra heat takes time to escape. Understandably, the process takes even longer if the coffee (ocean) continues being warmed as it is releasing heat. This is exactly what we see playing out in our climate system today. Therefore, it will take several decades for the climate to catch up to the warming expected for a given level of atmospheric carbon dioxide.

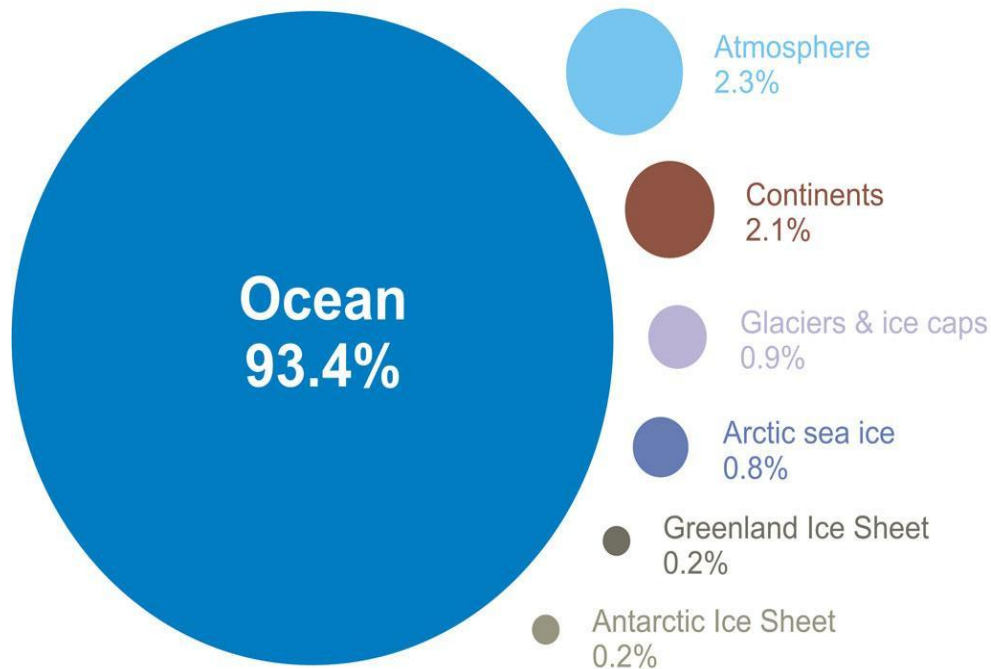


Figure 15: A breakdown of where the warming is going - components of global warming for the period 1993 to 2003 calculated from [IPCC AR4 5.2.2.3](#).

3a. It's Largely Irreversible

Up until recently, most scientists were working under the assumption that if we went cold turkey and brought CO₂ emissions to zero, CO₂ concentrations (measured in parts per million or ppm) in the atmosphere would peak and then be most of the way back down toward pre-industrial levels in about 100 to 200 years, with the warming decreasing along with them. A recent study, using a climate model known as an Earth-system model of intermediate complexity, or an *EMIC*, looked at how long it would take for the concentration and climate to head back down (Solomon et al., 2009). Because EMIC's are not as sophisticated as general circulation models, they have the advantage of being fast allowing researchers to run very long simulations of the Earth's climate. The goal of the experiment being to see what the atmosphere remembered of current human activities 1,000 years from now, in the year 3000. The experiment tested what would happen if CO₂ emissions suddenly stopped after peaking at different concentrations, ranging from 450 to 1,200 parts per million. In the model, CO₂ levels dropped so slowly that by the year 3000 the atmospheric concentration was still substantially above pre-industrial levels. Global temperatures also stayed high, which means that downstream impacts such as irreversible dry-season rainfall reductions in several regions comparable to those of the "Dust Bowl" era and inexorable sea level rise are also irreversible. This irreversibility is just one of the

reasons why the United States National Academy of Sciences recently highlighted the need for an effective national response, including “enacting policies and programs that reduce risk by limiting the cause of climate change and reducing vulnerability to its impacts” (NRC, 2011).

In conclusion, climate change is, in many respects, the ultimate procrastination problem. The longer we wait, the greater the risks we will face and the greater the costs will be to respond.

Summary

The four primary points of my testimony today are as follows:

1. Global warming is occurring and it continues to influence all facets of our climate system – the atmosphere, oceans, land surface and ice sheets. This is a well-established fact despite recent claims of a so-called global warming hiatus.
2. There is very high confidence that the climate change of the past 50 years is primarily due to human activities (Stott et al., 2010).
3. There is strong evidence that certain types of extreme weather events in the United States have become more frequent and/or intense - including heat waves and heavy downpours, and in some regions floods, wildfires and droughts. For other types of extremes, such as tornadoes, evidence is much more limited.
4. Weather extremes that can be physically linked to human-induced climate change will likely worsen if emissions globally are not reduced. Because of the long timescales of the ocean – the warming is largely irreversible.

Thank you.

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